JWST Telescope Integration and Test Status

Gary Matthews[a], Thomas Scorse[a], Scott Kennard[a], John Spina[a], Tony Whitman[a]
Scott Texter[b], Charles Atkinson[b], Greg Young[b]
Ritva Keski-Kuha[c], James Marsh[c], Juli Lander[c], Lee Feinberg[c]

[a]Exelis (United States), [b]Northrop Grumman Aerospace Systems (United States),
[c]NASA Goddard Space Flight Ctr. (United States)

ABSTRACT

The James Webb Space Telescope (JWST) is a 6.5m, segmented, IR telescope that will explore the first light of the universe after the big bang. 2014 is an incredible year for the Telescope Alignment, Integration, and Test portion of the program. Long awaited and planned, the two segment Pathfinder telescope will be built and the Optical Ground Support Equipment (OGSE) will be integrated into the large cryo-vacuum chamber at the Johnson Spaceflight Center. The current status of the integration equipment and the demonstrations leading up to the flight-like Pathfinder telescope will be provided as the first step to the final verification of the complex cryo test equipment. The plans and status of bringing the OGSE on-line and ready for a series of risk reduction cryo tests starting in 2015 on the Pathfinder Telescope will also be presented.

Keywords: JWST, Telescope, Alignment, Integration, Test

1. INTRODUCTION

The James Webb Space Telescope (Figure 1) is the successor to the Hubble Space Telescope. JWST will operate in the infrared region of the electromagnetic spectrum to allow the science community to observe far red shifted stars and galaxies as they were originally forming after the Big Bang 13.8 billion years ago. The scientists call JWST the first light machine since it will actually observe the first stars "turning on" and early galaxy formation. Even though the light from these early stars and galaxies was created billions of years ago, that light is just getting to our solar system now. They are moving away from us at nearly the speed of light Doppler-shifting the visible light into the infrared. In order to image this phenomenon, the telescope must also image in the infrared spectrum. This means that the telescope and all the systems that create that image must be very cold. That is why JWST operates at 40K. This extreme temperature creates many challenges for the engineers and scientists that are building and testing the observatory. This paper will provide an overview of the Alignment, Integration, and Test (AI&T) program and provide a recent status of this critical aspect of the JWST program.

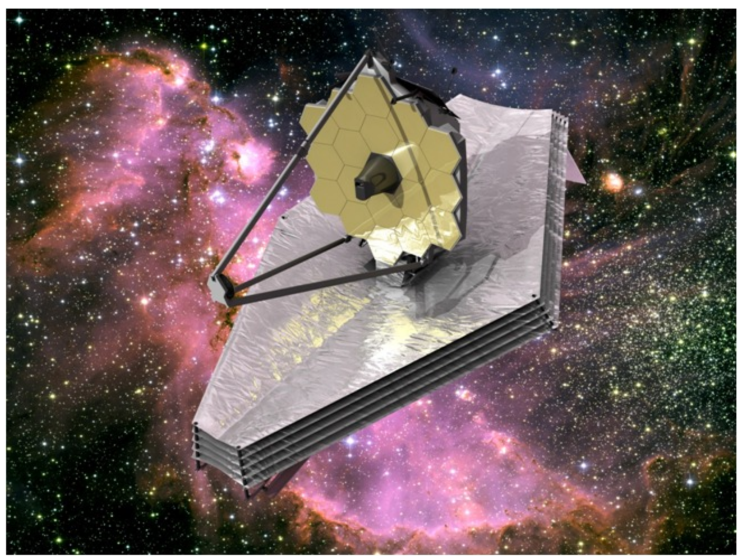

Figure 1 - The James Webb Space Telescope in it fully deployed configuration.

Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, edited by Jacobus M. Oschmann, Jr.,
Mark Clampin, Giovanni G. Fazio, Howard A. MacEwen, Proc. of SPIE Vol. 9143, 914305 · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2055286

2. ALIGNMENT, INTEGRATION, AND TEST

The AI&T phase of the program is fast approaching. But it has been in the planning stages since the inception of the program. It was recognized very early that the integration and test would be critical in the successful execution of the program. There are really two distinct aspects of JWST that are unique to the program – the optical configuration and operating temperature. The optical configuration for JWST represents the first space-based telescope that is segmented and deployable on orbit which provides a set of interesting challenges to be able to build an 18 segment primary mirror on Earth with the assurance that once on-orbit in zero gravity, it can be aligned to create a monolithic-like optical surface. The operating temperature is truly the biggest challenge for testing. In order to verify the performance, the largest cryogenic environmental test system in the world has been created. Given the fact that it takes a month to cool down and another two weeks to warm the system, a test configuration has been developed that will operate with the accuracy and dependability to satisfy the verification program.

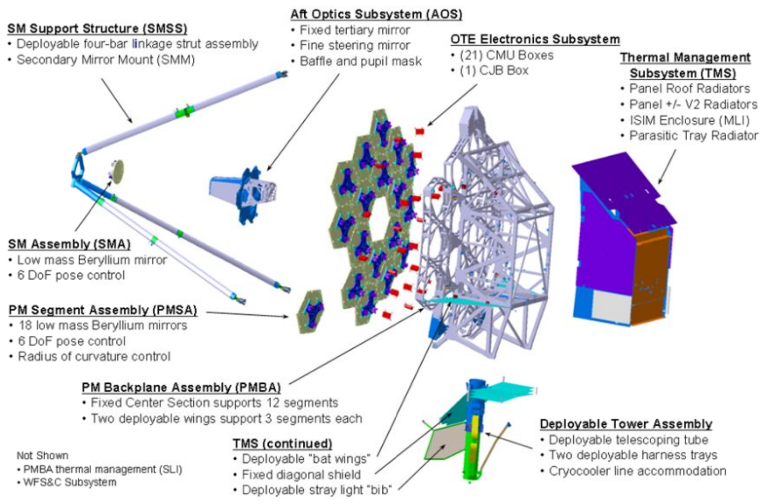

Figure 2 - The major components of the Optical Telescope Element are shown above.

The initial phase of the program will be to build what is called the Optical Telescope Element (OTE). This is the 6.5m telescope as shown in Figure 2. It is comprised of the large optical elements and the main structures that make up the system. Once the telescope is completed, the Integrated Science Instrument Module (ISIM) shown in Figure 3 is aligned and mated to the telescope. This major subsystem is called the OTIS which is comprised of the <u>OT</u>E and the <u>IS</u>IM.

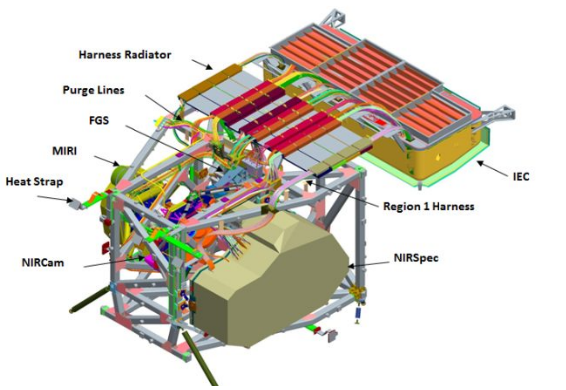

Figure 3 - The Integrated Science Instrument Module consists of the instrument assembly and the Integrated Electronics Compartment.

The final success of the AI&T portion of the program will be driven by careful planning and demonstrations prior to building the flight telescope and observatory to insure that the program can stay on plan during this critical path phase of the program

Figure 4 - The OTE and OTIS will be integrated in the SSDIF clean room at Goddard Space Flight Center.

3. TELESCOPE ALIGNMENT AND INTEGRATION

Building a 6.5m, segmented, deployable telescope is a unique undertaking requiring specialized equipment and processes. This activity will take place in the Goddard Space Flight Center Space Systems Development and Integration Facility (SSDIF) cleanroom (Figure 4). This large cleanroom was built for the Hubble Space Telescope and is now being fully utilized to build not only the JWST telescope, but also the ISIM. For telescope alignment and integration, a stable platform is required. This platform has to hold the telescope during integration and also provide assembly personnel the ability to reach and access to the telescope without causing the any motion or disturbance to the flight hardware. To accomplish this, two structures were actually built. The Ambient Optical Alignment Stand (AOAS) was designed and built in the SSDIF cleanroom. This is actually an optical bench that holds the telescope and another independent structure that holds the work platforms and other optical alignment hardware. An AOAS drawing with the telescope installed is shown in Figure 5. As can be seen, the telescope primary mirror is facing up during primary mirror integration. During alignment, the Primary Mirror Segment Assemblies (PMSA's) are attached to the Primary mirror Alignment and Integration Fixture (PAIF). This fixture provides the ability to move the mirror is 6 degrees of freedom for fine alignment and bonding in place.

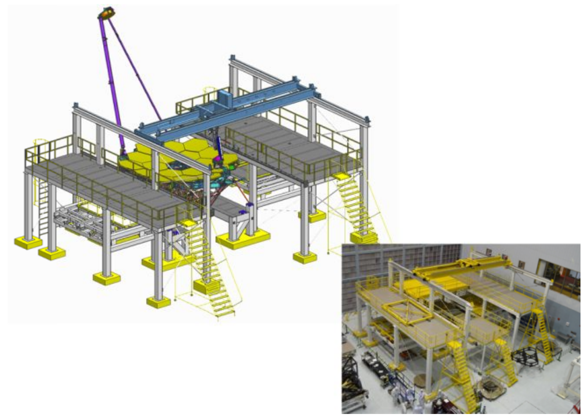

Figure 5 - The AOAS will be used to integrate the primary mirror segments into the JWST telescope.

There are many activities leading up to the actual alignment of the telescope. Initially, the PMSA is characterized on a Coordinate Measuring Machine (CMM) to understand where the optical surface is with respect to the telescope interfaces. In addition, the Primary Mirror Backplane Support Structure, PMBSS, is also characterized to understand the interfaces to PMSA's. All this data is combined to create a specialized tapered shim that is ground to precision tolerances such that the mirror will be in the proper location once it is in orbit.

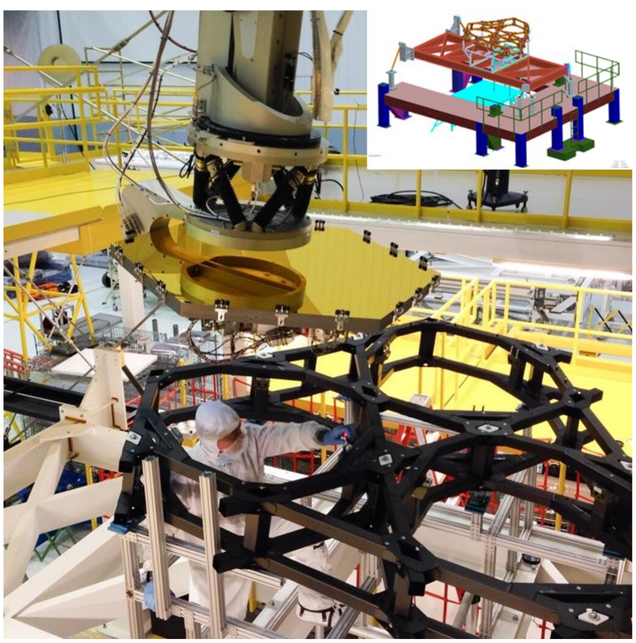

Figure 6 - The BSTA was used to provide a full demonstration of the primary mirror installation process.

To insure that this process if fully understood, there was a mirror handling demonstration completed in late 2013. A three segment simulator had been built earlier in the program to insure that the PMBSS would be stable over the large temperature changes that the flight structure would endure. The Backplane Stability Thermal Assembly (BSTA) was set up on the AOAS as shown in Figure 6 to allow a full mirror placement demonstration to occur.

The Engineering Development Unit (EDU) PMSA was measured on a CMM as shown in Figure 7. The results of the BSTA interface characterization were combined with the CMM measurements to create the custom shims used between the backplane simulator and the PMSA. Figures 6 and 7 show the technicians working on the mirror during the handling demonstration. The PAIF (Figure 6) can be seen holding the EDU mirror while work is being done to prepare for the alignment of the mirror from below.

The results of the mirror demonstration were very successful. One minor issue was discovered and was readily corrected with a redesigned fixture. One of the main reasons to do these early demonstrations is to discover these types of issues and correct them far off the critical path of the program. The next step in building up our confidence prior to building the flight OTE will be the Pathfinder program. During this effort, two spare PMSA's will be aligned and integrated into a flight-like PMBSS. This full dry run of the primary mirror alignment process will provide invaluable insight into building the flight OTE and will be a full dress rehearsal prior to starting the flight build in 2015.

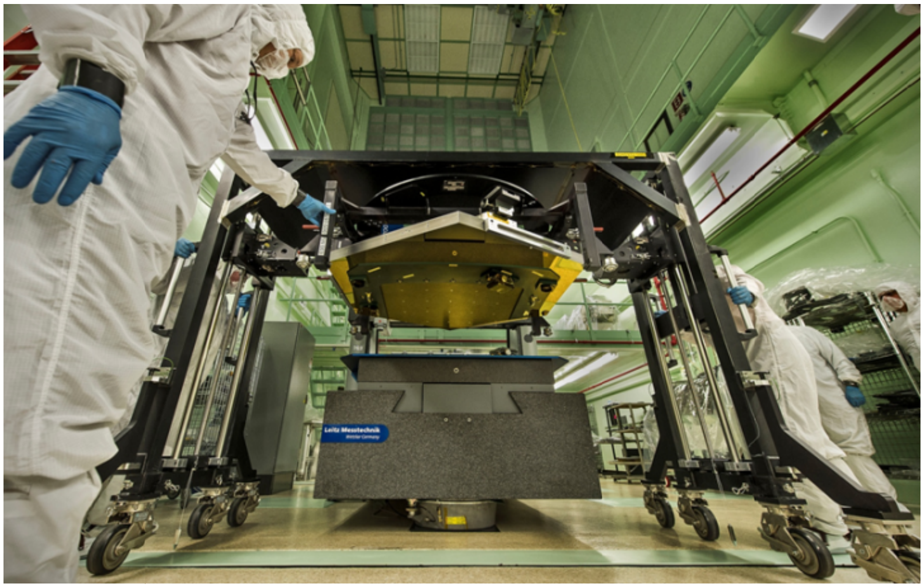

Figure 7 - The Engineering Development Unit PMSA is shown being installed on the CMM at the Goddard Space Flight Center

The Secondary Mirror Assembly (SMA) will be installed with the Secondary Mirror Support Structure (SMSS) in the stowed configuration as shown in Figure 8. A fixture called the Secondary Mirror Alignment and Integration Fixture (SAIF) will be used to install the secondary mirror. It has also has a six degree of freedom alignment functionality but since it will only be used once, the mechanisms are all manual. There are no full scale SMSS simulators available so the only rehearsal that has been possible for the SMA installation has been a small fixture that replicates the angles and configurations of the flight hardware. Out first real experience of aligning an SMA will be during the Pathfinder integration activities. This is still well ahead of the flight hardware so any issues can be resolved prior to the flight integration.

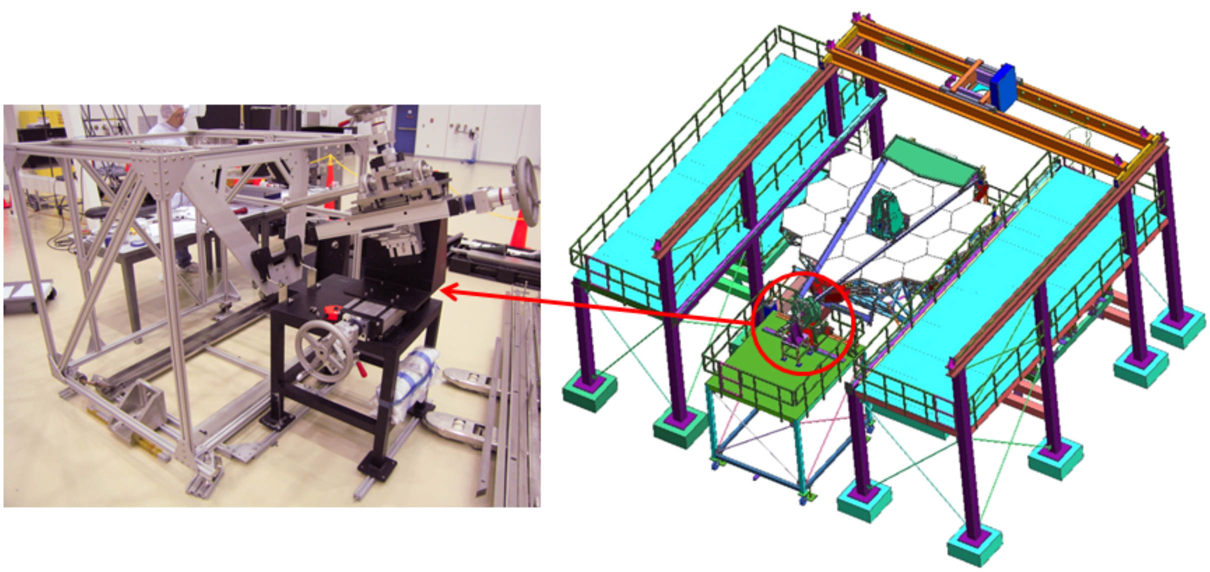

Figure 8 – The Secondary Mirror Assembly will be integrated with the Secondary Mirror Support Structure in the stowed configuration as shown. The Secondary Mirror Alignment and Integration Fixture will be used to position the secondary mirror into the flight structure.

4. OTIS ALIGNMENT AND INTEGRATION

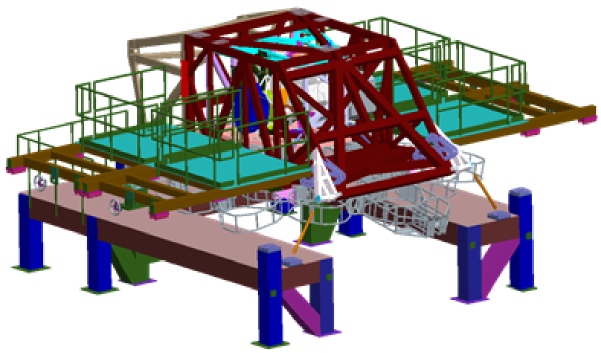

Figure 9 - The OTE is flipped over in the AOAS after mirror integration for ISIM installation

Once the OTE is completed, there are two major subassemblies left to install; the ISIM and the Integrated Electronics Compartment (IEC). The AOAS was designed to allow the OTE to be flipped for ISIM integration as shown in Figure 9. The IEC integration details are still being finalized but an integration and alignment demonstration for both of these assemblies is being planned. A replica of the Backplane Support Fixture (BSF) has been constructed as seen in Figure 10. This hardware will be used in early 2015 to practice the alignment and integration of the ISIM and IEC prior to the flight build.

Figure 10 - A full scale Backplane Support Frame has been constructed to demonstrate the integration of the ISIM onto the OTE.

5. OTIS TESTING

The environmental testing of the OTIS will happen at both Goddard Space Flight Center (GSFC) and at Johnson Spaceflight Center (JSC). The random vibration and acoustic testing will occur at GSFC prior to the OTIS shipment to JSC for cryo vacuum testing. The key test program is the cryogenic test program planned in JSC A Chamber. This chamber has just been refurbished and is the largest cryo vacuum chamber in the world and is capable of creating a flight-like 40K environment to test and verify the optical performance of the OTIS.
Much testing will be completed during the 90 day flight cryo test, but they can be described in three broad test types and are depicted in Figure 11:

1. Center of Curvature (CoC) Testing:
   The CoC test is completed from the center of curvature of the primary mirror. At this location, the test equipment can evaluate the entire primary mirror (PM) surface and insure that

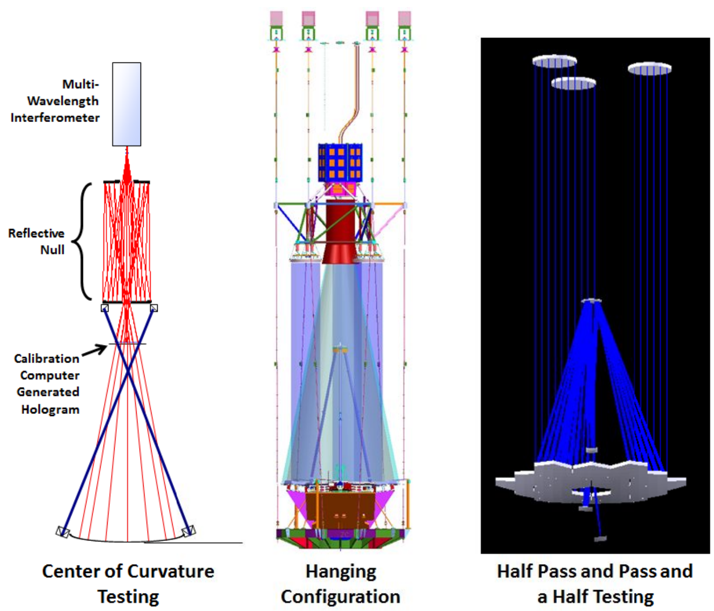

Figure 11 - The three basic test concepts can be seen here along with an overall view of the chamber configuration for testing.

the PM segments can be aligned, co-phased and figured as designed. The Center of Curvature Optical Assembly (COCOA) is placed at the center of curvature of the primary mirror and will be used to interrogate the 6.5m, primary mirror system.

2. Half Pass Testing:

   Using the Cassegrain focus location of the primary mirror and secondary mirror (SM) pair, an array of LED's pointed towards the focal plane instruments is used to fully illuminate the tertiary mirror (TM), fine steering mirror (FSM) and into the ISIM similar to what would be experienced with images from a distant star.

3. Pass and a Half Testing:

   This test also utilizes the Cassegrain focus location except that there are outward looking sources for this test. These sources reflect off the SM and the PM before hitting the three, 1.5m autocollimating flats (ACF) near the top of the chamber. The ACF's then send the image back to the PM and SM before being reflected off the TM and FSM and into the ISIM. One of the main aspects of the Pass and a Half test will be to check out the wavefront sensing and control aspects of the OTIS.

In order to accomplish these key test objectives, a comprehensive set of Optical Ground Support Equipment (OGSE) has been developed.

6. OGSE CONFIGURATION

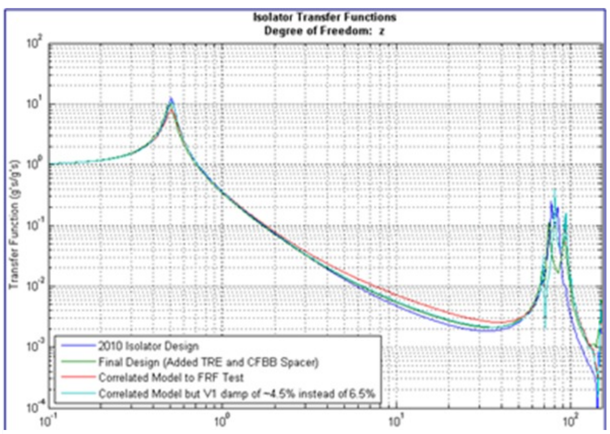

Figure 12 – The isolators have a first mode of 0.5Hz and can reduce the input by 20X-30X in the 1Hz - 60Hz area of interest.

Figure 13 shows the overall JSC cryo test configuration. Each of the main OGSE assemblies will be discussed below.

At the very top of the chamber are the six isolators (Figure 14) designed and built by Minus-K that support the hanging configuration including the OTIS. The isolators are tuned to a 0.5Hz first mode and can reduce the input disturbances by almost 30X (Figure 12). Hanging vertically from the six isolators are six vertical downrods that attach to the Upper Support Frame (USF).

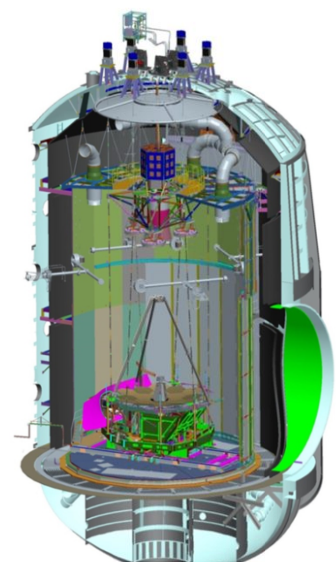

Figure 13 - The cryogenic test configuration is shown inside the JSC vacuum chamber.

The USF (Figure 15) is the structural part of what is known as the Autocollimating Flat/COCOA/USF (ACU) Assembly. The USF also supports the OTIS via six telescope rods that form a long hexapod to effectively lock the COCOA and ACF's to the OTIS which is critically important during optical testing.

Figure 14 - The Minus-K isolator is prepared for installation.

As discussed earlier, the COCOA (Figure 15) allows the test team to fully interrogate the segmented primary mirror. The two main parts of the COCOA are a multiwave interferometer (MWIF) developed by 4D and a two element reflective null manufactured by Photon Gear. The MWIF provides the phasing information required to understand the condition of the segmented primary mirror. A fully reflective null was required due to the wavelength of the interferometer that can vary from 10mm down to 660nm for final fine phasing.

There are three, 1.5m, Autocollimating flats (Figure 15) also attached to the USF. These assemblies can each be tipped and tilted with a set of three actuators on each ACF to allow the reflected beam to be steered back to the ISIM.

As discussed earlier, there are six long rods connected to the USF that connect the OTIS to the metrology equipment (COCOA and ACF's) together. The telescope rods do not connect to the OTIS directly but through the Hardpoint/Offloader Support Structure (HOSS). The HOSS (Figure 16) is a large weldment that provides various features that not only allow the OTIS to be mounted in a stable configuration, but also metrology features that provide data regarding pupil alignment and offloading features to minimize the effects of gravity.

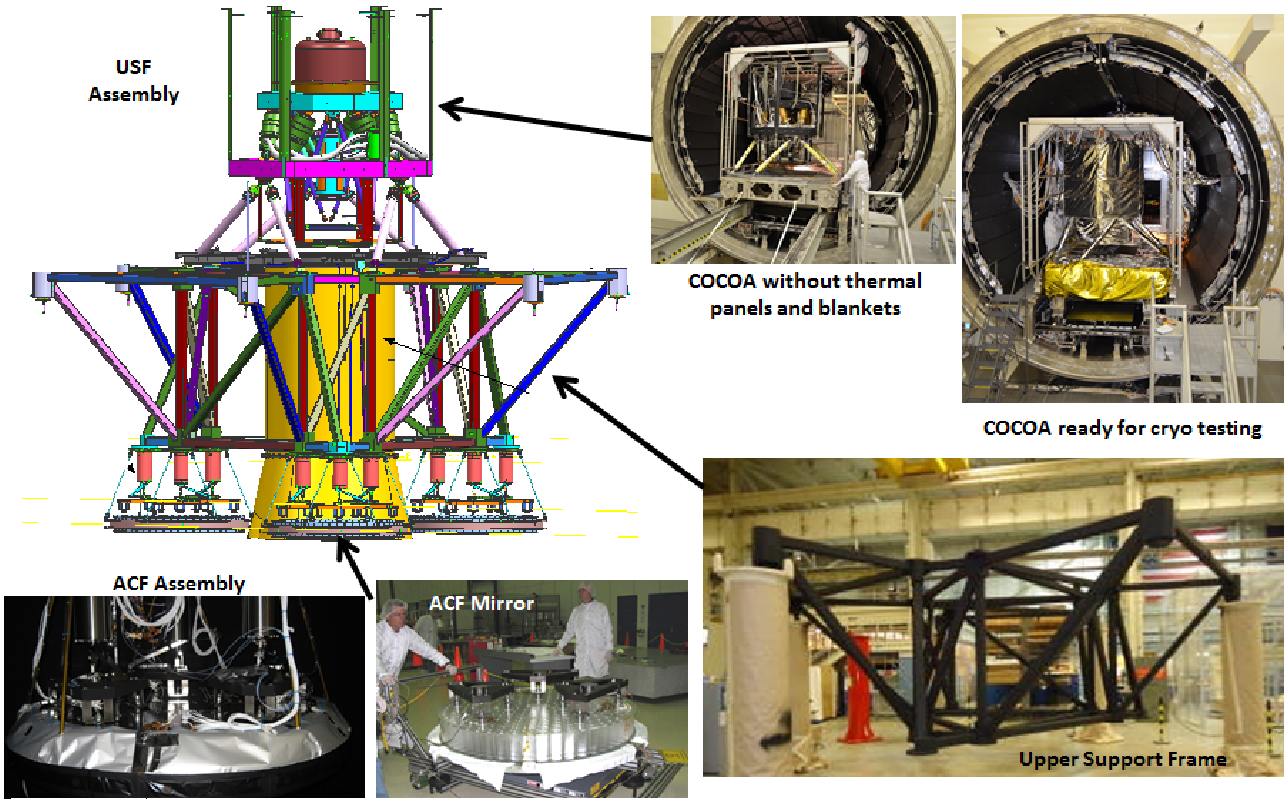

Figure 15 - The USF assembly consists of the Upper Support Frame, the COCOA, and the three ACF assemblies. This assembly is supported by the six downrods from the isolators at the top of the chamber and connects the OTIS to these optical metrology systems.

This entire system is called the Suspended OTIS Test System and it floats inside the JSC vacuum chamber within the 20K helium environment from the six isolators located at the top of the chamber. But the test team also needs to understand where everything is inside the test volume. That is accomplished with a system called the Cryo Position Metrology (CPM) system being designed and built by Johns Hopkins University Instrument Development Group.

Figure 16 - The HOSS supports the OTIS during cryo testing at JSC.

CPM is really two systems working in tandem. The first is a set of four photogrammetry (PG) camera systems on large windmills (Figure 17). The cameras are mounted on the ends of these windmills inside a pressure tight and heated enclosure. A set of coated windows allows the cameras to see the chamber without contaminating the cryo enclosure with stray light heat loss. The canisters provide two additional degrees of freedom to take pictures as the booms rotate through nearly 360 degrees. Small PG retroreflective targets are placed around the hardware along with precision scale bars. This allows us to understand the location of the OGSE and flight hardware to about 100 microns while at operating temperature. This process works very well for all the measurements that are needed except two. The absolute Radius of Curvature (RoC) and Primary Mirror Conic are two important metrics that are needed to insure that the telescope operates as designed. The PG system cannot measure that distance to the accuracy required. An Absolute Distance Measuring (ADM) system from Lieca is being used to measure this parameter. Basically, an ADM is the heart of laser trackers that are widely used by industry. In our case, the ADM was also mounted inside a pressure tight enclosure and mounted to the HOSS. From that location, the laser beam can be steered using two rotating Risely Prisms to a retroreflector mounted to the edge of a primary mirror segment and another one mounted to the computer generated hologram (CGH) on the COCOA. The location of the CGH is well known so the RoC and Conic can be calculated from the ADM information.

Figure 17 - One of the PG "windmill" systems is shown during testing by the Johns Hopkins Instrument Development Group at Oceaneering.

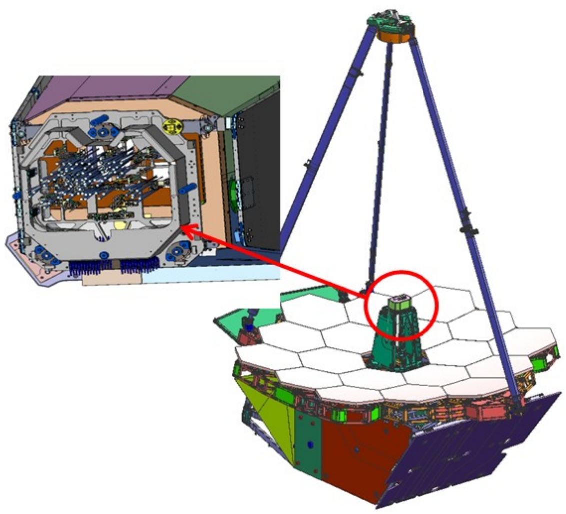

Figure 18 – The ASPA and its upward and downward sources are at the Cassegrain focus. The assembly attaches to the Aft Optics Assembly.

The last key piece of metrology equipment is the Aft Optics Subassembly Source Plate Assembly (ASPA) shown in Figure 18. As the name implies it is mounted to the Aft Optics Subassembly (AOS) on the telescope. This assembly is very close to the Cassegrain focus of the PM/SM pair. That location is the perfect location to inject inward and outward looking point sources to test the optical system. The ASPA provides the ability to test the entire OTIS in its flight configuration.

7. OGSE INTEGRATION STATUS

Almost all the OGSE is completed at this point in time and the job of integrating all of the equipment into the JSC vacuum chamber is in process. The chamber was completed in early 2014 and integration started immediately in order to be ready for cryo testing of the two mirror Pathfinder in January 2015.

The integration plan is outlined below with expected completion dates:

- Chamber Rail System Load Test – Completed March 2014
- Chamber and Clean Room cleaning and certification – Completed April 2014
- Installation of the PG system – Completed May 2014

- USF Cryo Load Test – June 2014
- Chamber Bake Out with USF and HOSS – July 2014
- ACU Assembly Build – August 2014
- ACU Chamber Installation – September 2014
- HOSS 2X Cryo Load Test, Chamber Certification, and Chamber Commissioning – October 2014
- Chamber ready for Pathfinder – December 2014
- Optical Ground Support Equipment Cryo Test #1 – January 2015

8. PATHFINDER CRYO TESTING

As part of our cryo test development program, the JWST team has created a series of cryogenic vacuum tests using what is called the Pathfinder telescope. The Pathfinder (Figure 19) uses two flight spare primary mirror segments (the Engineering Development Unit and one of the flight spare mirrors from the outer ring of the telescope). The Pathfinder also uses the flight spare secondary and a replica of the flight structure center section. This assembly will be integrated in the summer of 2014 and delivered to JSC for a series of three cryo tests. These tests are defined below:

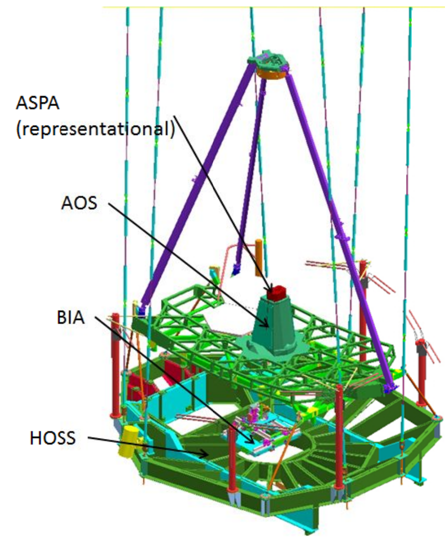

Figure 19 - The Pathfinder telescope will use two of the flight spare mirrors, the flight spare secondary mirror and the flight aft optics assembly to allow early testing using the optical ground support equipment.

- Chamber Commissioning

  This test occurs prior to the Pathfinder delivery to JSC. This is an initial test to insure that the OGSE is operational and the hardware has basic functionality.
  - Does the COCOA mechanisms operate as designed
  - Does the ACF actuators move the flat as commanded
  - Does the photogrammetry system provide data as commanded
  - Does the chamber get as cold as design with no obvious heat leaks
- OGSE#1 (Optical Ground Support Equipment Test #1)

  This initial test will verify the COCOA can phase and figure the two primary mirror segments. Photogrammetry will continue to be exercised and data processing techniques refined.

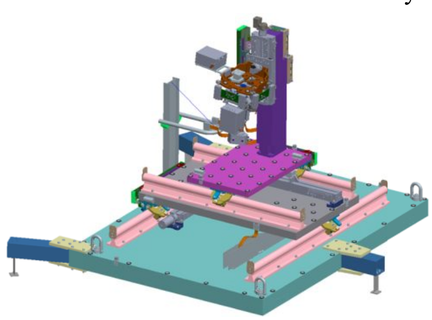

Figure 20 - The BIA is a surrogate instrument that will be used during OGSE#2 to verify the half pass and pass and a half test process.

- OGSE#2

This test brings in the flight Aft Optics Assembly and a flight detector simulator called the Beam Image Analyzer (BIA) shown in Figure 20. The BIA will be used in the half pass and pass and a half test simulations as an end to end test of the telescope. All the OGSE will be operated during this test and will provide a high degree of confidence that the test equipment is ready for the OTIS test.

- Thermal Pathfinder

The final Pathfinder attempts to simulate all of the thermal aspects that will be present in the OTIS test. The cool down and warm up scenarios will be simulated as will the various heat sources that will be present in the flight system.

9. SUMMARY

The early demonstrations and the Pathfinder Alignment, Integration, and Test program will provide an excellent basis for process development and early detection of AI&T problems. This early resolution of processes, procedures, and hardware debug will enallble a high degree of confidence as the program enters the OTE and OTIS alignment and integration tasks and the OTIS starts the environmental test phase. All of these are on the critical path of the program and any delays will impact our ability to deliver the OTIS for Spacecraft integration and test. The integration process is well underway at JSC and by Fall 2014, a complete test system will be ready for Pathfinder testing in January 2015.

REFERENCES

[1] **Optomechanical integration and alignment verification of the James Webb Space Telescope (JWST) optical telescope element**
Conrad Wells, Matthew Coon, ITT Space Systems Division (United States)
Published in Proceedings Volume 7433: August 2009

[2] **The center of curvature optical assembly for the JWST primary mirror cryogenic optical test: optical verification**
Conrad Wells, Gene Olczak, Cormic Merle, Tom Dey, Mark Waldman, Tony Whitman, Eric Wick, Aaron Peer, ITT Corp. Geospatial Systems (United States)
Published in Proceedings Volume 7790: August 2010

[3] **Architecting a revised optical test approach for JWST**
Charlie Atkinson, Jonathan Arenberg, Northrop Grumman (United States); Gary Matthews, Mark Waldman, Alan Wertheimer, Tony Whitman, ITT (United States); Jim Oschmann, Ball Aerospace& Technologies Corp. (United States)
Published in Proceedings Volume 7010: August 2008

[4] **The center of curvature optical assembly for the JWST primary mirror cryogenic optical test**
Conrad Wells, Gene Olczak, Cormic Merle, Tom Dey, Mark Waldman, Tony Whitman, Eric Wick, Aaron Peer, ITT Geospatial Systems (United States)
Published in Proceedings Volume 7739: July 2010

[5] **JWST's cryogenic position metrology system**
Tony L. Whitman, ITT Exelis Geospatial Systems (United States); Randolph P. Hammond, Joe Orndorff, Stephen Hope, Stephen A. Smee, The Johns Hopkins Univ. (United States); Thomas Scorse, Keith A. Havey, Jr., ITT Exelis Geospatial Systems (United States)
Published in Proceedings Volume 8442: August 2012

[6] **The integration and test program of the James Webb Space Telescope**
Randy A. Kimble, Pamela S. Davila, Charles E. Diaz, Lee D. Feinberg, Stuart D. Glazer, NASA Goddard Space Flight Ctr. (United States); Gregory S. Jones, Northrop Grumman Aerospace Systems (United States); James M. Marsh, NASA Goddard Space Flight Ctr (United States); Gary W. Matthews, ITT Exelis Geospatial Systems (United States); Douglas B. McGuffey, NASA Goddard Space Flight Ctr. (United States); Patrick H. O'Rear, NASA Johnson Space Flight Ctr. (United States); Deborah D. Ramey, NASA Goddard Space Flight Ctr. (United States); Carl A. Reis, NASA Johnson Space Flight Ctr. (United States); Scott C. Texter, Northrop Grumman Aerospace Systems (United States); Tony L. Whitman, ITT Exelis Geospatial Systems (United States)
Published in Proceedings Volume 8442: August 2012

[7] **Assembly integration and ambient testing of the James Webb Space Telescope primary mirror**
Conrad Wells, Tony Whitman, John Hannon, Art Jensen, Eastman Kodak Co. (United States)
Published in Proceedings Volume 5487: October 2004

[8] **Integration and verification of the James Webb Space Telescope**
Charles B. Atkinson, Pat Harrison, Northrop Grumman Corp. (United States); Gary Matthews, Eastman Kodak Co. (United States); Paul Atcheson, Ball Aerospace& Technologies Corp. (United States)
Published in Proceedings Volume 5180: December 2003

[9] **James Webb Space Telescope system cryogenic optical test plans**
Lee D. Feinberg, NASA Goddard Space Flight Ctr. (United States); Allison Barto, Ball Aerospace& Technologies Corp. (United States); Mark Waldman, Sigma Space Corp. (United States); Tony Whitman, ITT Corp. Geospatial Systems (United States)
Published in Proceedings Volume 8150: September 2011

[10] **James Webb Space Telescope primary mirror integration: testing the multiwavelength interferometer on the test bed telescope**
Gene Olczak, David J. Fischer, Mark Connelly, Conrad Wells, ITT Corp. Geospatial Systems (United States)
Published in Proceedings Volume 8146: September 2011